14 RESPIRATION IN PLANTS

Respiration is an energy releasing enzymatically controlled catabolic process which involves a step-wise oxidative breakdown of food substances inside living cells. It takes place in all types of living cells, even the photosynthetic ones that trap solar energy and store the same in food. Photosynthesis provides food material not only to green cells but to all nongreen cells, tissues and organs of green plants. Translocation is required for this. Animals are heterotrophs. Some animals called **herbivores** directly obtain food from plants. Other animals feed on herbivores. They are known as carnivores. Decaying organic matter provides food to saprophytes like many fungi and bacteria. Food reaches every cell of an organism for respiration to take place. Therefore, actual respiration is also called cellular respiration. During cellular respiration food substances are oxidised. It occurs in cytoplasm and mitochondria. Chemical bonds (*e.g.*, C—C) are broken during oxidation. Breaking of chemical bonds releases energy.

Cellular respiration, *i.e.*, oxidative breakdown of food materials within the cell, releases energy and biochemical intermediates. This energy is used in the synthesis of ATP. The biochemical intermediates are used for the synthesis of organic compounds that take part in growth, repair and metabolism. Every living cell oxidises its food to release energy. About 50% of the energy liberated during cellular respiration is used for synthesis of biomolecules and other life activities like absorption of minerals, maintenance of cell permeability, uptake of materials from other cells, osmotic work, growth, development, cell division, muscular contraction, nervous conduction, overcoming entropy, movement, etc. (Fig. 14.1). The remaining energy is dissipated as heat. The latter is not useless, but helps in keeping the body warm. Rise in body temperature during excercise is caused by higher amount of energy being dissipated as heat. Energy is not released in a single step in respiration nor it is directly used for various cellular activities. Instead energy is liberated in controlled fashion in several steps and is mostly stored in ATP molecules. Thus 114.5 kcal of energy is liberated for each molecule of oxygen used in respiration. It is employed in synthesis of 6 molecules of ATP.

$$ADP + H_3PO_4 + \text{Energy (8.15 kcal)} \rightleftharpoons ATP\,(ADP \sim P)$$

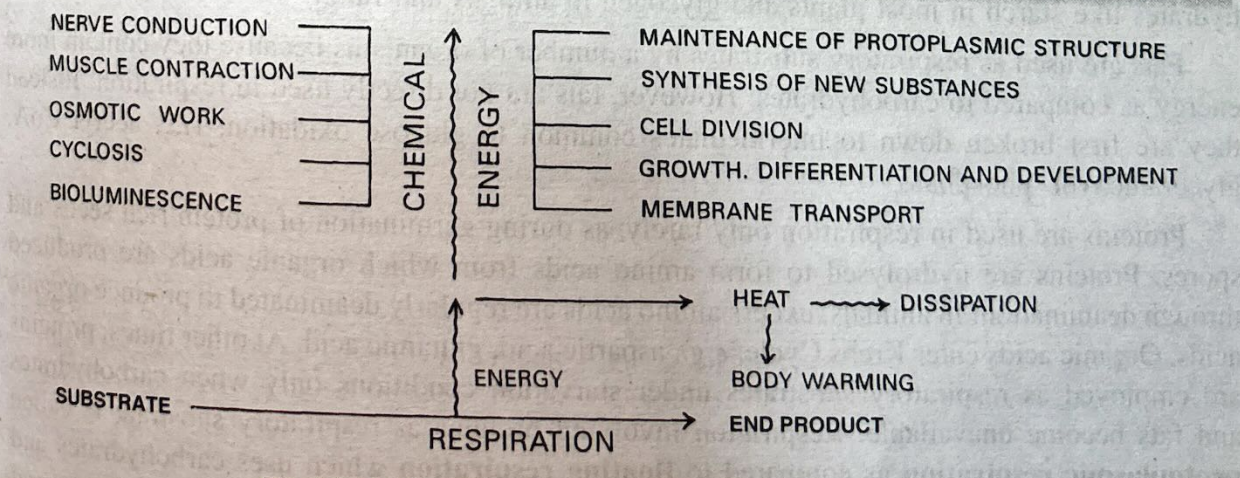


Fig. 14.1. Utilisation of respiratory energy by living systems.

ATP is broken down to release energy whenever and wherever energy needs to be utilized. This energy stored in ATP is utilised for carrying out different cellular activities. Thus ATP acts as the **energy currency** of the cell.

As pointed out by Lavosier, both combustion (*e.g.*, burning of coal, wood, oil, etc.) and respiration are similar in (a) Breakdown of complex organic substances, (b) Utilization of oxygen, (c) Evolution of carbon dioxide and water, (d) Release of energy. Combustion is a nonenzyme and uncontrolled release of energy which mostly occurs as heat and to a lesser extent as light. Combustion and respiration differ in several aspects.

Differences between Respiration and Combustion (Burning or Fire)

Respiration	*Combustion (Burning)*
1. It occurs inside living cells.	1. It is a noncellular process.
2. It is under biological control.	2. Combustion is an uncontrolled process.
3. Respiration is a biochemical process.	3. Combustion is a physico-chemical process.
4. Energy is released in stages as chemical bonds are broken in steps.	4. Energy is released in a single step as all chemical steps occur simultaneously.
5. Less than 50% energy is liberated as heat.	5. Most of the energy is liberated as heat.
6. Light is liberated in a very few cases.	6. Light is produced during combustion.
7. Temperature is not allowed to rise.	7. Temperature becomes very high.
8. Most of the energy is trapped in ATP molecules.	8. ATP is not formed.
9. Oxidation occurs at the end of reaction (terminal oxidation) between reduced coenzymes and oxygen.	9. The substrate is directly oxidised in combustion.
10. A number of intermediates are formed. They are used in the synthesis of different organic compounds.	10. No intermediates are produced in combustion.
11. A number of enzymes are required, one for each step or reaction.	11. Burning is a nonenzymatic process.

Respiratory Substrates

Respiratory substrates are those organic substances which are oxidised during respiration to liberate energy inside the living cells. The common respiratory substrates are carbohydrates, proteins, fats and organic acids. The most common respiratory substrate is **glucose**. It is a hexose monosaccharide. Another related compound is fructose. Glucose is formed from storage carbohydrates like starch in most plants and glycogen in animals and fungi.

Fats are used as respiratory substrates by a number of organisms because they contain more energy as compared to carbohydrates. However, fats are not directly used in respiration. Instead they are first broken down to intermediates common to glucose oxidation, *viz.*, acetyl CoA, glyceraldehyde phosphate.

Proteins are used in respiration only rarely, as during germination of protein rich seeds and spores. Proteins are hydrolysed to form amino acids from which organic acids are produced through deamination. In animals, excess amino acids are regularly deaminated to produce organic acids. Organic acids enter Krebs Cycle, *e.g.*, aspartic acid, glutamic acid. At other times, proteins are employed as respiratory substrates under starvation conditions only when carbohydrates and fats become unavailable. Respiration involving proteins as respiratory substrate is called **protoplasmic respiration** as compared to **floating respiration** which uses carbohydrates and fats. Protoplasmic respiration cannot be continued for long as it depletes protoplasm of structural and functional proteins as well as liberates toxic ammonia.

Differences between Floating and Protoplasmic Respiration

Floating Respiration	*Protoplasmic Respiration*
1. It is a common mode of respiration.	1. It is a rare mode of respiration.
2. The substrate is carbohydrate or fat.	2. The substrate is protein.
3. The substrate is a storage material which is hydrolysed for respiration.	3. The substrate is storage material only in some seeds. In others it is part of the protoplasm.
4. It goes on indefinitely throughout the life of the cells.	4. It occurs only for some period when carbohydrate or fat is not available as during starvation.
5. Toxic products are not formed.	5. Toxic products like ammonia are produced.
6. It keeps the cells healthy.	6. It kills the cells ultimately.

Gaseous Exchange

Lavosier observed that in respiration of animals, oxygen is taken in from the air. In return they give out carbon dioxide and water. This O_2–CO_2 gaseous exchange occurs not only between the organism and its environment but also between every cell and its surrounding environment. An animal cell exchanges gases with the extracellular fluid while a plant cell does so with the air present in intercellular spaces. An organism shows exchange of gases in a liquid or gaseous environment depending upon the habitat. However, some organisms, especially micro-organisms, do not require oxygen for their respiration. Some of them give out CO_2 while a few do not do so. In these organisms there is no gaseous exchange.

Do Plants Breathe ?

Plants require oxygen for respiration and release carbon dioxide. For this gaseous exchange, they unlike animals, have no specialised organs. It occurs through stomata and lenticels.

Reasons for Absence of Respiratory Organs in Plants

1. Each part of plant takes care of its own gas exchange needs. There is little transport of gases from one part to another.

2. Plants do not require much demands for gas exchange. All plant parts respire at rates far lower than animals.

3. Leaves are well adapted to take care of their own needs of gases during photosynthesis. Moreover, leaves also utilize oxygen released during photosynthesis.

4. In plants, cells are closely packed and located quite close to the surface of the plant. Thus the distance that gases must diffuse is not large.

5. In stems, the living cells are present beneath the bark and are in contact with air through lenticels.

6. Loose parenchyma cells in leaves, stem and roots provide interconnecting network of air spaces for quick gas exchange.

Thus most cells of a plant have atleast one part of their surface in contact with air.

Types

Respiration is of two main types, **aerobic** and **anaerobic**. Aerobic respiration is that type of respiration in which organic food is completely oxidised with the help of oxygen (as terminal oxidant) into carbon dioxide and water.

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{\text{Enzymes}} 6CO_2 + 6H_2O + 686\,\text{kcal/2870 kJ}$$

686 kcal or 2870 kJ of energy is liberated per mole of glucose. The value was previously calculated to be 673 kcal. One kcal is equal to 1000 calories. It is that amount of energy (as heat) which can raise the temperature of one litre of water by 1°C.

Anaerobic respiration is a type of respiration where oxygen is not used as an oxidant and the organic food is broken down incompletely to liberate energy without oxygen being used as oxidant. Energy is liberated during breaking of bonds between various types of atoms. The common products of anaerobic respiration are CO_2, ethyl alcohol and lactic acid.

$$C_6H_{12}O_6 \xrightarrow{\text{Enzymes}} 2\,CO_2 + \underset{\text{ethyl alcohol}}{2C_2H_5OH} + 59\ \text{kcal/247 kJ}$$

$$C_6H_{12}O_6 \xrightarrow{\text{Enzymes}} \underset{\text{lactic acid}}{2\,C_3H_6O_3} + 36\ \text{kcal/150 kJ}$$

Anaerobic respiration is the only mode of respiration in some micro-organisms. In higher organisms it occurs as a temporary measure. Anaerobic respiration cannot continue for long in higher organisms because (i) It yields small amount of energy. (ii) More substrate is decomposed so that little is left for growth and repair. (iii) Some of the end products and intermediates of anaerobic respiration are toxic in higher concentration. (iv) Several physiological processes of higher organisms are linked to aerobic respiration, *e.g.*, active absorption of minerals, protoplasmic streaming, etc.

Compensation Point

It is that value or point in light intensity and atmospheric CO_2 concentration when the rate of photosynthesis is just equivalent to the rate of respiration in the photosynthetic organs so that there is no net gaseous exchange. The value of light compensation point is 2.5–100 ft candles for shade plants and 100–400 ft candles for sun plants. The value of CO_2 compensation point is 25–100 ppm (25–100 $\mu l.l^{-1}$) in C_3 plants and less than 5 ppm (5 $\mu l.l^{-1}$) in C_4 plants. A plant cannot survive for long at compensation point because there is net loss of organic matter due to respiration of nongreen organs and dark respiration.

Respiratory Quotient (RQ)

Respiratory quotient is the ratio of the volume of carbon dioxide produced to the volume of oxygen consumed in respiration over a period of time. Its value can be one, zero, more than 1 or less than one.

$$RQ = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ absorbed}}$$

RQ Equal to Unity

Respiratory quotient is unity if carbohydrate is respiratory substrate and the respiration is aerobic.

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6\,CO_2 + 6H_2O \qquad RQ = 6CO_2/6O_2 = 1$$

RQ Less than Unity

RQ is less than one when respiration is aerobic but the respiratory substrate is either fat or protein. RQ is about 0.7 for most of the common fats. It occurs during germination of fatty seeds.

$$\underset{\text{triolein}}{C_{57}H_{104}O_6} + 80\,O_2 \longrightarrow 57\,CO_2 + 52\,H_2O \qquad RQ = 57\,CO_2/80\,O_2 = 0.71$$

$$\underset{\text{tripalmitin}}{2(C_{51}H_{98}O_6)} + 145\,O_2 \longrightarrow 102\,CO_2 + 98\,H_2O \qquad RQ = 102\,CO_2/145\,O_2 = 0.7$$

RQ is about 0.9 in case of proteins, peptones, etc.

R.Q. Zero

Succulents do not evolve carbon dioxide during night (when their stomata are open) as the same is used in carbon fixation. They also change carbohydrates to organic acids which utilise oxygen but do not evolve carbon dioxide.

$$2C_6H_{12}O_6 + 3O_2 \longrightarrow \underset{\text{malic acid}}{3C_4H_6O_5} + 3H_2O \qquad \text{R.Q.} = \text{Zero } CO_2/3O_2 = \text{Zero}$$

RQ More than Unity

(a) RQ slightly more than unity is found when organic acids are broken down as respiratory substrates under aerobic conditions, *e.g.*,

$$\underset{\text{oxalic acid}}{2(COOH)_2} + O_2 \longrightarrow 4CO_2 + 2H_2O \qquad RQ = 4\,CO_2/1\,O_2 = 4.0$$

$$\underset{\text{malic acid}}{C_4H_6O_5} + 3\,O_2 \longrightarrow 4\,CO_2 + 3H_2O \qquad RQ = 4CO_2/3O_2 \text{ or } 1.3$$

$$\underset{\text{succinic acid}}{2C_4H_6O_4} + 7O_2 \longrightarrow 8CO_2 + 6H_2O \qquad RQ = 8CO_2/7O_2 \text{ or } 1.14$$

(b) In anaerobic respiration there is no consumption of oxygen. Carbon dioxide is produced in most of the cases. Therefore, respiratory quotient is infinity. Carbohydrate is the usual substrate.

$$C_6H_{12}O_6 \xrightarrow{\text{zymase}} 2CO_2 + 2C_2H_5OH \qquad RQ = 2CO_2/\text{Zero } O_2 \text{ or infinity}$$

An intermediate value is obtained where an organ is undergoing both aerobic and anaerobic modes of respiration.

Importance. (i) Knowledge of respiratory quotient helps in determining respiratory substrate. (ii) It helps in knowing the type of respiration being performed. (iii) It provides some information about major transformation of food materials. (iv) RQ values indicate that living organisms seldom use a single respiratory substrate. It is usually more than one.

Aerobic Respiration

Aerobic respiration is an enzymatically controlled release of energy in a stepwise catabolic process of complete oxidation of organic food into carbon dioxide and water with oxygen acting as terminal oxidant. It occurs by two methods, common pathway and pentose phosphate pathway. **Common Pathway.** It is known so because its first step, called **glycolysis**, is common to both aerobic and anaerobic modes of respiration. The common pathway of aerobic respiration consists of three steps— glycolysis, Krebs cycle and terminal oxidation.

Glycolysis (Gk. *glycos* - sugar, *lysis* – splitting, Fig. 14.2)

It is also called **EMP pathway** because it was discovered by three German scientists— Gustav Embden, Otto Meyerhof and J. Parnas in 1930. Glycolysis is the process of partial oxidation of glucose or similar hexose sugar into two molecules of pyruvic acid through a series of **ten enzyme mediated** reactions releasing some energy (as ATP) and reducing power (as $NADH_2$). It occurs in cytosol or cytoplasm. Glycolysis is common to both aerobic and anaerobic modes of respiration. It is the first stage of breakdown of glucose in aerobic respiration and the only step in glucose breakdown in anaerobic respiration. Glycolysis has two phases, preparatory and pay off. In the preparatory phase glucose is broken down to glycerealdehyde 3-phosphate. In the pay off phase the latter is changed into pyruvate producing NADH and ATP.

(Preparatory Phase (Energy Spending Phase)

1. **Phosphorylation of Glucose.** Respiratory substrate (glucose or fructose) is formed by hydrolysis of starch or sucrose. Hydrolysis of starch occurs with the help of enzymes amylase and maltase. It yields glucose. Sucrose is hydrolysed by enzyme invertase to form glucose and fructose. Glucose is phosphorylated to glucose-6-phosphate by ATP in the presence of enzyme **hexokinase** (Meyerhof, 1927) or glucokinase (*e.g.*, liver) and Mg^{2+}.

$$\text{Glucose} + \text{ATP} \xrightarrow[Mg^{2+}]{\text{hexokinase}} \text{Glucose-6-phosphate} + \text{ADP}$$

2. **Synthesis of Fructose 6-phosphate.** Glucose-6-phosphate is changed to its isomer fructose-6-phosphate with the help of enzyme phosphohexose isomerase

$$\text{Glucose 6-phosphate} \underset{Mg^{2+}}{\overset{\text{Phosphohexose Isomerase}}{\rightleftharpoons}} \text{Fructose 6-phosphate}$$

Fructose 6-phosphate can also be produced directly by phosphorylation of fructose with the help of enzyme fructokinase.

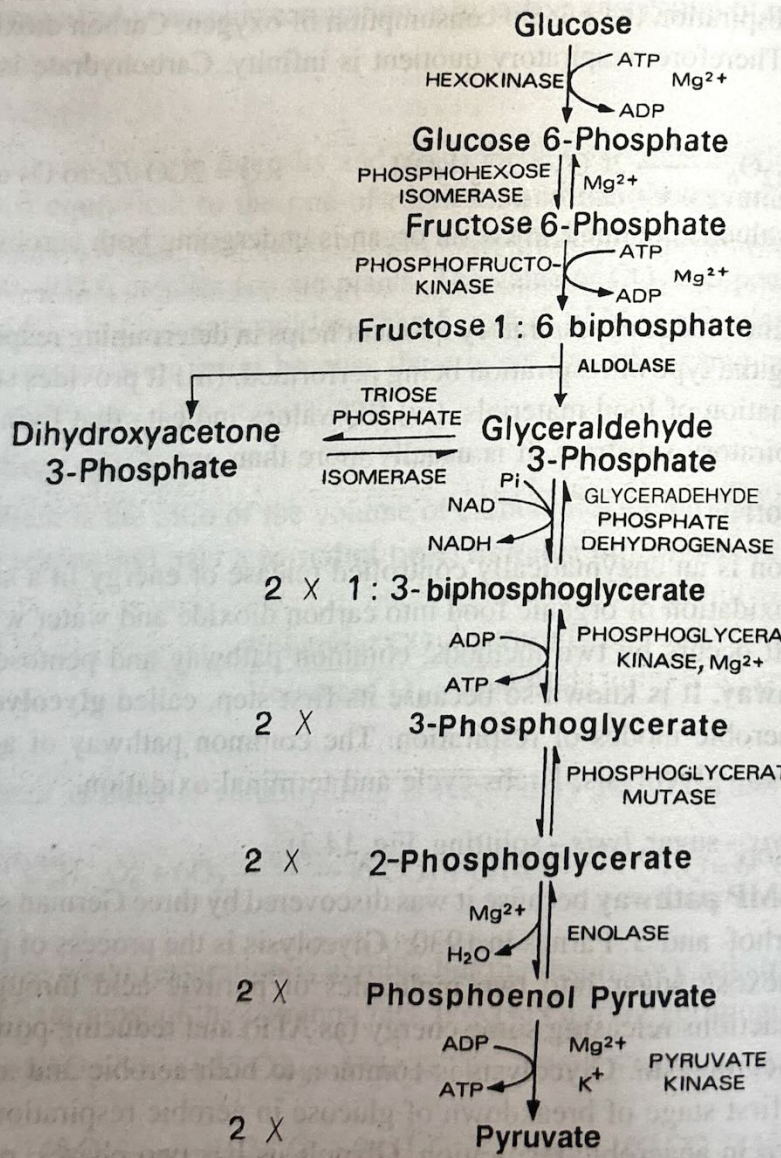


Fig. 14.2 Schematic representation of glycolysis or EMP pathway.

$$\text{Fructose} + \text{ATP} \xrightarrow[Mg^{2+}]{\text{Fructokinase}} \text{Fructose 6-phosphate} + \text{ADP}$$

3. **Formation of Fructose 1, 6-Biphosphate**. Fructose 6-phosphate is further phosphorylated by means of ATP in presence of enzyme phosphofructo-kinase and Mg^{2+}. The product is fructose 1 : 6 biphosphate.

$$\text{Fructose 6-phosphate} + \text{ATP} \xrightarrow[+Mg^{2+}]{\text{Phosphofructokinase}} \text{Fructose 1 : 6 biphosphate} + \text{ADP}$$

In plants a pyrophosphate (ppi) dependent phosphofructokinase has been discovered (Kruger, 1997) which carries out conversion of fructose 6-phosphate into fructose 1, 6-biphosphate.

4. **Splitting**. Fructose 1 : 6 biphosphate splits up enzymatically to form one molecule each of 3-carbon compounds, glyceraldehyde 3- phosphate (= GAP or 3-phosphoglyceraldehyde =PGAL) and dihydroxy acetone 3-phosphate (DiHAP).

$$\text{Fructose 1 : 6 biphosphate} \xrightarrow{\text{Aldolase}} \text{Glyceraldehyde 3-phosphate (GAP) or Phosphyglyceraldehyde (= PGAL)} + \text{Dihydroxyacetone 3-phosphate}$$

5. **Isomerisation of DiHAP**. Dehydroxyacetone 3-phosphate is isomerised to glyceraldehyde 3-phosphate with the help of enzyme triose phosphate isomerase.

$$\text{Dihydroxy acetone 3-phosphate} \underset{}{\overset{\text{Triose phosphate isomerase}}{\rightleftharpoons}} \text{Glyceraldehyde 3-phosphate}$$

Pay Off Phase (Energy Conserving Phase)

6. **Oxidation and Phosphorylation**. In the presence of enzyme glyceraldehyde 3-phosphate dehydrogenase, the glyceraldehyde 3-phosphate is oxidised through removal of hydrogen and addition of phosphate from inorganic source to form 1 : 3 biphosphoglycerate. NAD^+ is hydrogen acceptor. It produces NADH.

$$\text{Glyceraldehyde 3-phosphate} + H_3PO_4 + NAD^+ \underset{}{\overset{\text{Glyceraldehyde Phosphate Dehydrogenase}}{\rightleftharpoons}} \text{1 : 3 biphosphoglycerate} + NADH + H^+$$

7. **Substrate Level Phosphorylation (Formation of ATP)**. One of the two phosphates of biphosphoglycerate is linked by high energy bond. It can synthesise ATP and form 3-phosphoglycerate. The enzyme is phosphoglycerate kinase. The direct synthesis of ATP from metabolites is called **substrate level phosphorylation**.

$$\text{1:3 biphosphoglycerate} + \text{ADP} \underset{+ Mg^{2+}}{\overset{\text{Phosphoglycerate kinase}}{\rightleftharpoons}} \text{3-phosphoglycerate} + \text{ATP}$$

8. **Isomerization**. 3-phosphoglycerate is changed to its isomer 2-phosphoglycerate by enzyme phosphoglyceromutase.

$$\text{3-phosphoglycerate} \underset{}{\overset{\text{Phosphoglyceromutase}}{\rightleftharpoons}} \text{2-phosphoglycerate}$$

9. **Dehydration**. Through the agency of enzyme enolase, 2-phosphoglycerate is converted to phosphoenol pyruvate (PEP). A molecule of water is removed in the process. Mg^{2+} is required.

$$\text{2-phosphoglycerate} \underset{Mg^{2+}}{\overset{\text{Enolase}}{\rightleftharpoons}} \text{Phosphoenol Pyruvate (PEP)} + H_2O$$

10. **Formation of Pyruvate**. During formation of phosphoenol pyruvate, the phosphate radical picks up energy. It helps in the production of ATP by **substrate level phosphorylation**. The enzyme is pyruvate kinase. It produces pyruvate from phosphoenol pyruvate.

$$\text{Phosphoenol pyruvate} + \text{ADP} \xrightarrow[Mg^{2+},\ K^{+}]{\text{Pyruvate kinase}} \text{Pyruvate} + \text{ATP}$$

Net Products of Glycolysis. In glycolysis two molecules of ATP are consumed during double phosphorylation of glucose to form fructose 1 : 6 biphosphate. In return four molecules of ATP are produced by substrate level phosphorylation (conversion of 1 : 3 biphosphoglycerate to 3-phosphoglycerate and phosphenol pyruvate to pyruvate). Two molecules of $NADH_2$ are formed at the time of oxidation of glyceraldehyde 3-phosphate to 1 : 3 biphosphoglycerate. The net reaction is as follows :

$$\text{Glucose} + 2\text{NAD}^{+} + 2\,\text{ADP} + 2\text{H}_3\text{PO}_4 \rightarrow 2\,\text{Pyruvate} + 2\,\text{NADH} + 2\text{H}^{+} + 2\text{ATP}$$

Each NADH is equivalent to 3 ATP, so that the net gain in glycolysis is 8 ATP.

Intermediates of glycolysis are used for synthesis of important biochemicals. For example, phosphoenol pyruvate yields shikimic acid which is used in synthesis of amino acids, tryptophan, tyrosine and phenylalanine. Tryptophan is raw material for IAA synthesis. The amino acids are employed for synthesis of proteins, alkaloids, flavonoids and lignin. Similarly, pyruvic acid forms amino acid alanine.

Krebs Cycle or Tricarboxylic Acid Cycle (Fig. 14.3)

The cycle was discovered by Hans Krebs (1937, 1940, Nobel Prize 1954). It occurs inside matrix of mitochondria. The cycle is also named as **citric acid cycle** (CAC) or **tricarboxylic acid (TCA) cycle** after the initial product. *Krebs cycle is stepwise oxidative and cyclic degradation of activated acetate derived from pyruvate.*

Oxidation of Pyruvate to Acetyl-CoA. Pyruvate enters mitochondria through a specific transport protein. It undergoes **oxidative decarboxylation** to produce CO_2 and NADH. The product combines with sulphur containing coenzyme A to form acetyl CoA or activated acetate. The reaction occurs in the presence of an enzyme complex pyruvate dehydrogenase (made up of a decarboxylase, lipoic acid, TPP, transacetylase and Mg^{2+}). This step is called **link reaction** or transition reaction or gateway step as it links glycolysis with Krebs cycle.

$$[\text{Pyruvate} + \text{NAD}^{+} + \text{CoA} \xrightarrow[Mg^{2+}]{\text{Pyruvate Dehyrogenase}} \text{Acetyl~CoA} + \text{NADH} + \text{H}^{+} + \text{CO}_2\ \uparrow] \times [2]$$

Acetyl CoA functions as **substrate entrant** for Krebs cycle. It is also the **connecting link** between glycolysis and Krebs cycle. The **acceptor molecule** of Krebs cycle is a 4-carbon compound oxaloacetate. Kerbs cycle involves two decarboxylations and four dehydrogenations (oxidations). The various **components of ten stepped Krebs cycle** are as follows :

1. **Formation of Citrate**. Acetyl CoA (2-carbon compound) combines with oxalo-acetate(4-carbon compound) in the presence of condensing enzyme citrate synthase to form a tricarboxylic 6-carbon compound called citric acid. It is the **first product** of Krebs cycle. CoA is liberated.

$$\text{Acetyl CoA} + \text{Oxaloacetate} + \text{H}_2\text{O} \xrightarrow{\text{Citrate Synthase}} \text{Citrate} + \text{CoA} \qquad \times [2]$$

2. **Formation of Isocitrate**. Citrate undergoes reorganisation in the presence of iron containing enzyme aconitase first forming *cis* aconitate and releasing water.

$$\text{Citrate} \underset{Fe^{+2}}{\overset{\text{Aconitase}}{\rightleftharpoons}} \textit{cis}\text{-aconitate} + H_2O \qquad \times [2]$$

cis-aconitate is then converted into isocitrate with the addition of water while attached to enzyme aconitase. This results in interchange of hydrogen and hydroxyl groups in the molecule.

$$\textit{cis}\text{-aconitate} + H_2O \underset{Fe^{+2}}{\overset{\text{Aconitase}}{\rightleftharpoons}} \text{Isocitrate} \qquad \times [2]$$

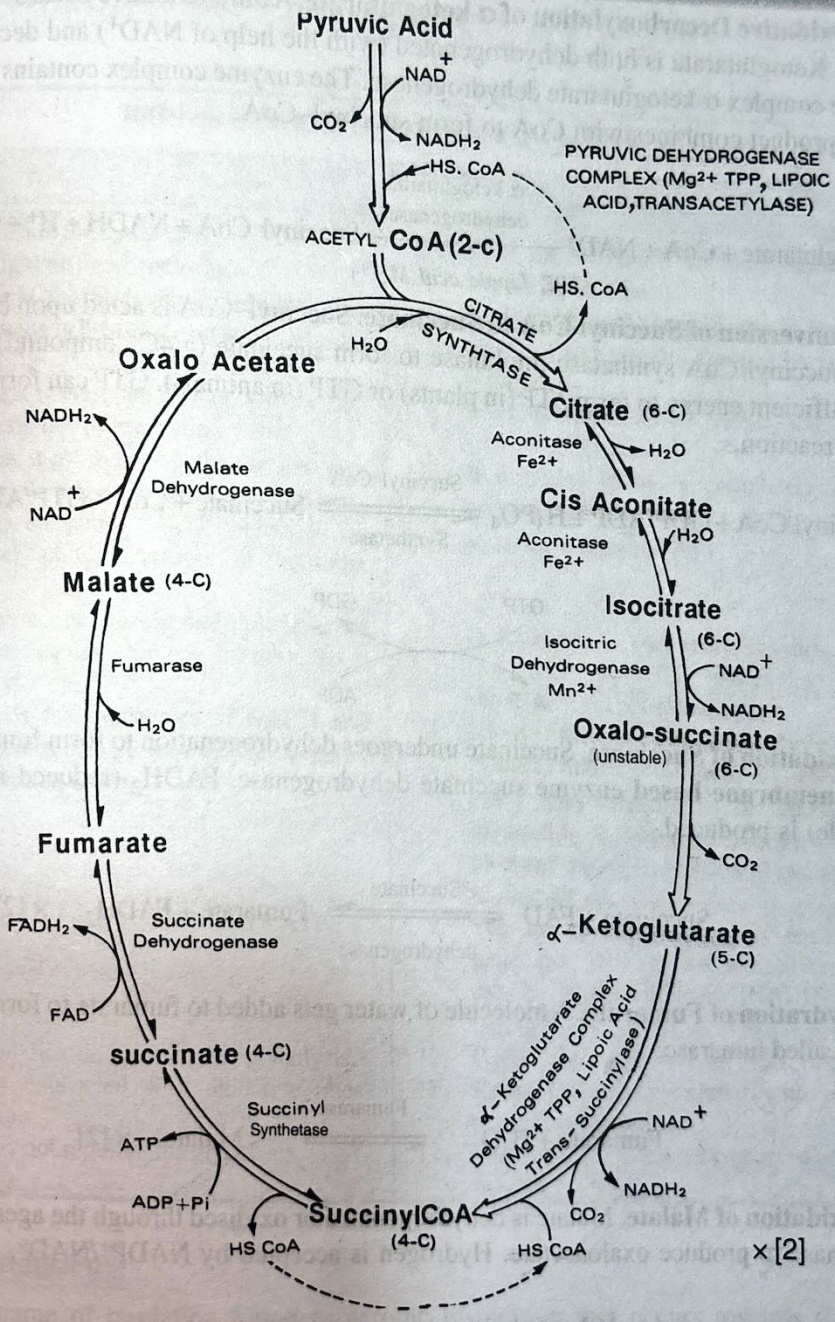


Fig. 14.3. Schematic representation of Krebs cycle or TCA cycle.

3. **Formation of α-ketoglutarate.** Isocitrate undergoes oxidative decarboxylation in the presence of enzyme isocitrate dehydrogenase and Mn^{2+}. A transient oxalosuccinate is formed as intermediate. It undergoes decarboxylation to form 5–carbon α-ketoglutarate or 2–oxoglutarate. NADH (NADPH according to some workers) is produced.

$$\text{Isocitrate} + NAD^+ \underset{+\ Mn^{2+}}{\overset{\text{Isocitrate Dehydrogenase}}{\rightleftharpoons}} \text{Oxalosuccinate} + NADH + H^+ \quad \times [2]$$

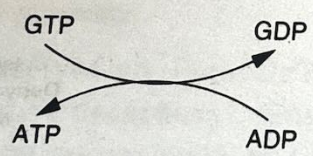
$$\text{Oxalosuccinate} \longrightarrow \alpha\text{-Ketoglutarate} + CO_2 \uparrow \quad \times [2]$$

4. **Oxidative Decarboxylation of α-ketoglutarate.** A third oxidative decarboxylation occurs when α - Ketoglutarate is both dehydrogenated (with the help of NAD^+) and decarboxylated by an enzyme complex α-ketoglutarate dehydrogenase. The enzyme complex contains TPP and lipoic acid. The product combines with CoA to form succinyl~CoA.

$$\alpha\text{-Ketoglutarate} + CoA + NAD^+ \xrightarrow[(TPP,\ Lipoic\ acid\ Mg^{2+})]{\alpha\text{-ketoglutarate dehydrogenase}} \text{Succinyl CoA} + NADH + H^+ + CO_2 \uparrow \quad \times [2]$$

5. **Conversion of Succinyl CoA to Succinate**. Succinyl~CoA is acted upon by enzyme succinate or succinyl CoA synthetase thiokinase to form succinate (a 4C compound). The reaction releases sufficient energy to form ATP (in plants) or GTP (in animals). GTP can form ATP through a coupled reaction.

$$\text{Succinyl CoA} + GDP/ADP + H_3PO_4 \underset{\text{Synthetase}}{\overset{\text{Succinyl CoA}}{\rightleftharpoons}} \text{Succinate} + CoA + GTP/ATP \quad \times [2]$$



6. **Oxidation of Succinate**. Succinate undergoes dehydrogenation to form fumarate with the help of a **membrane based** enzyme succinate dehydrogenase. $FADH_2$ (reduced flavin adenine dinucleotide) is produced.

$$\text{Succinate} + FAD \underset{\text{dehydrogenase}}{\overset{\text{Succinate}}{\rightleftharpoons}} \text{Fumarate} + FADH_2 \quad \times [2]$$

7. **Hydration of Fumarate**. A molecule of water gets added to fumarate to form malate. The enzyme is called fumarase.

$$\text{Fumarate} + H_2O \overset{\text{Fumarase}}{\rightleftharpoons} \text{Malate} \quad \times [2]$$

8. **Oxidation of Malate**. Malate is dehydrogenated or oxidised through the agency of malate dehydrogenase to produce oxaloacetate. Hydrogen is accepted by $NADP^+/NAD^+$.

$$\text{Malate} + NAD\,(P)^+ \overset{\text{Malate Dehydrogenase}}{\rightleftharpoons} \text{Oxaloacetate} + NAD\,(P)H + H^+ \quad \times [2]$$

Oxaloacetate picks up another molecule of activated acetate to repeat the cycle. A molecule of pyruvic acid that enters a mitochondrion is completely oxidised to form 3 carbon dioxide in one pre-Krebs cycle decarboxylation and two Krebs cycle decarboxylations.

$$\text{Pyruvic acid} + 4\,NAD^+ + FAD + 2H_2O + ADP + Pi \rightarrow 3\,CO_2 + 4\,NADH + 4\,H^+ + FADH_2 + ATP \times [2]$$

A molecule of glucose yields two molecules of $NADH_2$, 2ATP and two pyruvate while undergoing glycolysis. The two molecules of pyruvate are completely degraded in Krebs cycle to form two molecules of ATP, $8NADH_2$, and $2FADH_2$.

$$\text{Glucose} + 4\,ADP + 4\,H_3PO_4 + 10\,NAD^+ + 2FAD \longrightarrow 6\,CO_2 + 4\,ATP + 10\,NADH + 10\,H^+ + 2\,FADH_2$$

Differences between Glycolysis and Krebs Cycle

Glycolysis	*Krebs Cycle*
1. It occurs inside the cytoplasm.	1. Krebs cycle operates inside mitochondria.
2. It is a straight or linear pathway.	2. It is a cyclic pathway.
3. Glycolysis is the first step of respiration in which glucose is broken down to the level of pyruvate.	3. Krebs cycle is the second step in respiration where an active acetyl group is broken down completely.
4. The process is common to both aerobic and anaerobic modes of respiration.	4. It occurs only in aerobic respiration.
5. It degrades a molecule of glucose into two molecules of an organic substance, pyruvate.	5. It degrades pyruvate completely into inorganic substances ($CO_2 + H_2O$).
6. Glycolysis consumes 2 ATP molecules for the initial phosphorylation of substrate molecule.	6. It does not consume ATP.
7. In glycolysis, one glucose molecule liberates 4 ATP molecules through substrate level phosphorylation.	7. In Krebs cycle, two acetyl residues liberate two ATP or GTP molecules through substrate level phosphorylation.
8. Net gain is two molecules of NADH and two molecules of ATP for every molecule of glucose broken down.	8. Krebs cycle produces six molecules of NADH, and 2 molecules of $FADH_2$ for every two molecules of Acetyl CoA oxidised by it. Two molecules of NADH are liberated during conversion of two pyruvates to Acetyl CoA.
9. The net gain of energy is equal to 8 ATP.	9. The net gain of energy is equal to 24 molecules of ATP. Six molecules of ATP can be produced from $2NADH_2$ formed during dehydrogenation of two pyruvates.
10. No carbon dioxide is evolved in glycolysis.	10. Carbon dioxide is evolved in Krebs cycle.
11. It is not connected with oxidative phosphorylation.	11. Krebs cycle is connected with oxidative phosphorylation.
12. Oxygen is not required for glycolysis.	12. Krebs cycle uses oxygen as terminal oxidant.

Terminal Oxidation

It is the name of oxidation found in aerobic respiration that occurs towards the end of catabolic process and involves the passage of both electrons and protons of reduced coenzymes to oxygen. It produces water.

$$NADH + H^+ \rightleftharpoons NAD^+ + 2H^+ + 2e^-$$

$$FADH_2 \rightleftharpoons FAD + 2H^+ + 2e^-$$

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \longrightarrow H_2O$$

Terminal oxidation consists of two processes— electron transport and oxidative phosphorylation.

Electron Transport Chain (Fig. 14.4)

Inner mitochondrial membrane contains groups of electron and proton transporting enzymes. In each group the enzymes are arranged in a specific series called **electron transport chain** (ETC) or **mitochontrial respiratory chain** or **electron transport system** (ETS). An electron transport chain or system is a series of coenzymes and cytochromes that take part in the passage of electrons from a chemical to its ultimate acceptor. The passage of electrons from one enzyme or cytochrome to the next is a downhill journey with a loss of energy at each step. At each step the electron carriers include flavins, iron sulphur complexes, quinones and cytochromes. Most of them are prosthetic groups of proteins. Quinones are highly mobile electron carriers. Inner mitochondrial membrane possesses five complexes. Complex V is connected with ATP synthesis (F_0–F_1 particle). Complexes I to IV are involved in electron transport— (i) NADH-Q reductase or NADH-dehydrogenase complex, (ii) Succinate Q-reductase complex, (iii) QH_2-cytochrome *c* **reductase complex**, (iv) **Cytochrome *c* oxidase complex**.

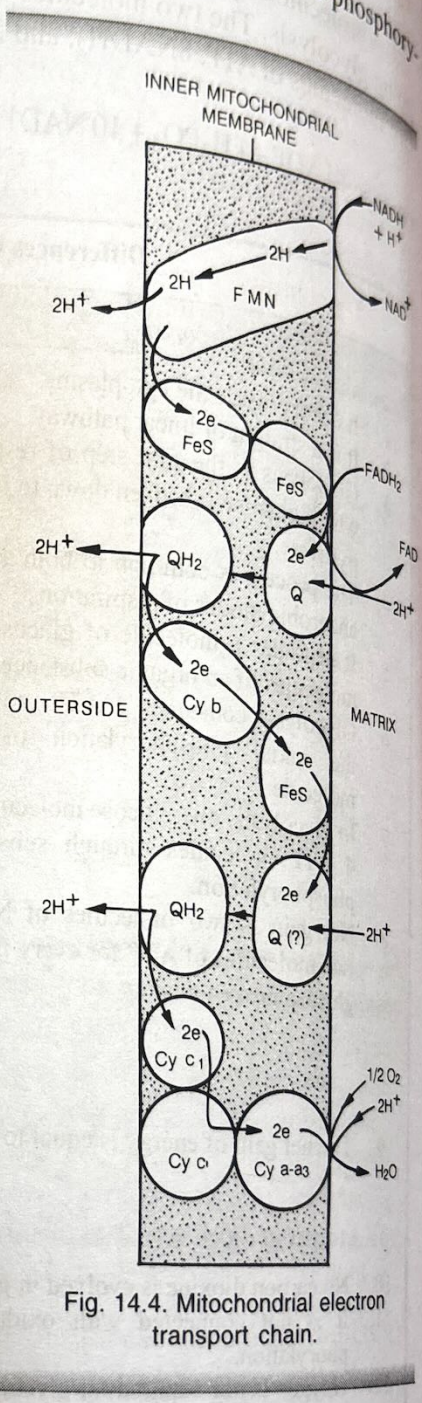


Fig. 14.4. Mitochondrial electron transport chain.

NADH-Q reductase (or NADH-dehydrogenase) has two prosthetic groups, flavin mononucleotide (FMN) and iron sulphur (Fe-S) complexes. Both electrons and protons pass from NADH to FMN. The latter is reduced. However, $FMNH_2$ breaks to release protons (H^+) and electrons.

$$NADH + H^+ + FMN \longrightarrow FMNH_2 + NAD^+$$

$$FMNH_2 \longrightarrow FMN + 2H^+ + 2e^-$$

Electron now moves to the FeS complex and from there to a quinone. The common quinone is co-enzyme Q, also called ubiquinone (UQ).

$$2e^- + 2Fe^{3+}S \longrightarrow 2Fe^{2+}S$$

$$2Fe^{2+}S + Q \longrightarrow 2Fe^{3+}S + Q^{2-}$$

Charged ubiquinone picks up protons and passes it into the outer chamber with the help of Cyt *b*.

$FADH_2$ produced during reduction of succinate also hands over its electrons and protons to ubiquinone or co-enzyme Q through FeS complex. The enzyme is succinate-Q reductase complex.

$$FADH_2 + 2Fe^{3+}\,S \longrightarrow 2\,Fe2 + S + 2H^+ + FAD$$

$$2Fe^{2+}\,S + Q + 2H^+ \longrightarrow 2\,Fe^{3+}\,S + QH_2$$

QH_2-cytochrome *c* reductase complex has three components— cytochrome *b*, FeS complex and cytochrome c_1. Coenzyme Q may also be involved between FeS complex and cytochrome c_1. Reduced ubiquinone or ubiquinol (QH_2) is oxidised with the passage of protons to the outside and handing over the electrons to cytochrome *c* via cytochrome b–c_1 complex.

$$QH_2 + 2Fe^{3+}\text{ cyt. } b \longrightarrow Q + 2H^+ + 2\,Fe^{2+}\text{ cyt. } b$$

$$2\,Fe^{2+}\text{ cyt. } b + 2\,Fe^{3+}\,S \longrightarrow 2\,Fe^{3+}\text{ cyt. } b + 2\,Fe^{2+}\,S$$

$$2\,Fe^{2+}\,S + Q + 2H^+ \longrightarrow 2\,Fe^{3+}\,S + QH_2\,(?)$$

$$QH_2 + 2\,Fe^{3+}\text{ cyt. } c_1 \longrightarrow Q + 2H^+ + 2\,Fe^{2+}\text{ cyt. } c_1$$

Cytochrome c_1 hands over its electron to a small protein called cytochrome *c*. Like co-enzyme Q, cytochrome *c* is also mobile carrier of electrons that transfers electrons between complex III and IV.

$$2\,Fe^{2+}\text{ cyt. } c_1 + 2\,Fe^{3+}\text{ cyt. } c \rightarrow 2\,Fe^{3+}\text{ cyt. } c_1 + 2\,Fe^{2+}\text{ cyt. } c$$

Cytochrome *c* oxidase complex contains cytochrome *a* and cytochrome a_3. Cytochrome a_3 also possesses two copper centres. The latter help in transfer of electron to oxygen.

$$2\,Fe^{2+}\text{ cyt.}c + 2\,Fe^{3+}\text{ cyt. } a \longrightarrow 2\,Fe^{3+}\text{ cyt.}c + 2\,Fe^{2+}\text{ Cyt. } a$$

$$2\,Fe^{2+}\text{ cyt.}a + 2Fe^{3+}\text{ cyt.}a_3\,Cu^{2+} \longrightarrow 2\,Fe^{3+}\text{ cyt.}a + 2\,Fe^{2}\text{ cyt.}a_3Cu^{2+}$$

$$2Fe^{2}\text{ cyt.}a_3\,Cu^{2+} \longrightarrow 2\,Fe^{3}\text{ cyt.}a_3Cu^{1+}$$

$$2Fe^{3}\text{ cyt.}a_3Cu^{1+} + [O] \longrightarrow 2Fe^{3}\text{ cyt.}a_3Cu^{2+} + [O^{2-}]$$

Oxygen is the ultimate acceptor of electrons. It becomes reactive and combines with protons to form **metabolic water**.

$$2H^+ + O^{2-} \longrightarrow H_2O$$

Energy released during passage of electrons from one carrier to the next is made available to specific transmembrane complexes, which pump protons (H^+) from the matrix side of the inner mitochondrial membrane to the outer chamber. There are three such sites corresponding to three enzymes present in the electron transport chain (NADH-Q reductase, QH_2-cytochrome *c* reductase and cytochrome *c*-oxidase). This increases proton concentration in the outer chamber or outer surface of the inner mitochondrial membrane. It creates a proton gradient. The difference in the proton concentration on the outer and inner sides of the inner mitochondrial membrane creates an electric potential across the membrane with inner surface becoming negative as compared to outer surface. The electrochemical potential gradient created across the membrane due to high H^+ concentration on one side is called **proton motive force** (PMF, Δp).

Oxidative Phosphorylation (Fig. 14.5)

Oxidative phosphorylation is the synthesis of energy rich ATP molecules with the help of energy liberated during oxidation of reduced co-enzymes (NADH, $FADH_2$) produced in respiration. The enzyme required for this synthesis is called **ATP synthase**. It is considered to be **fifth complex** of electron transport chain. ATP synthase is located in F_1 or head piece of F_0–F_1 or elementary particles. The particles are present in the inner mitochondrial membrane. ATP-synthase becomes active in ATP formation only where there is a **proton gradient** having higher concentration of H^+ or protons on the F_0 side as compared to F_1 side (chemiosmotic hypothesis of Peter Mitchell, 1961, Nobel Prize in 1978). Increased proton concentration is produced in the

outer chamber or outer surface of inner mitochondrial membrane by the pushing of protons with the help of energy liberated by passage of electrons from one carrier to another. Transport of the electrons from NADH over ETC helps in pushing three pairs of protons (5 pairs as per latest estimate) to the outer chamber while two (latest estimate–three) pairs of protons are sent outwardly during electron flow from $FADH_2$ (as the latter donates its electrons further down to the ETC).

Higher proton concentration in the outer chamber causes the protons to pass inwardly into matrix or inner chamber through the inner membrane. The latter possesses special rotating proton channels in the region of F_0 (base) of the F_0 — F_1 particles. The flow of protons through the F_0 channel induces F_1 particle to function as ATP-synthase. The energy of the proton gradient is used in attaching a phosphate radicle to ADP by high energy bond. This produces ATP. Oxidation of one molecule of $NADH_2$ produces 3 ATP molecules while a similar oxidation of $FADH_2$ forms 2 ATP molecules.

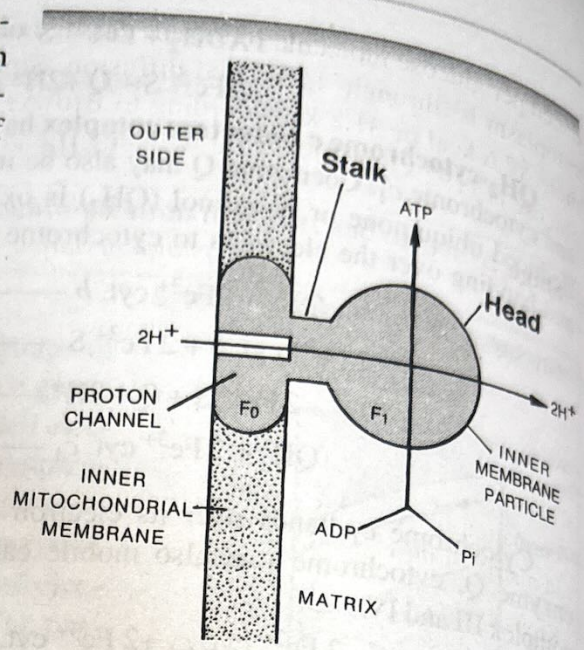


Fig. 14.5. ATP synthesis by F_0— F_1 particle.

Balance Sheet of ATP

There is net gain of 2 ATP molecules during glycolysis and 2 ATP (GTP) molecules during double Krebs cycle. Glycolysis also forms 2 $NADH_2$. Its reducing power is transferred to mitochondria for ATP synthesis. For this a shuttle system operates at the inner mitochondrion membrance. (i) $NADH_2 \rightarrow NAD \rightarrow NADH_2$. (ii) $NADH_2 \rightarrow FAD \rightarrow FADH_2$. The former operates in liver, heart and kidney cells. No energy is spent. The second method occurs in muscle and nerve cells. It lowers the energy level of $2NADH_2$ by 2ATP molecules. A total of 10 $NADH_2$ and 2 $FADH_2$ molecules are formed in aerobic respiration. They help in formation of 34 ATP molecules. The net gain from complete oxidation of a molecule of glucose in muscle and nerve cells is 36 ATP molecules (10 $NADH_2$ = 30 ATP, 2 $FADH_2$ = 4 ATP, four formed by substrate level phosphorylation in glycolysis and Krebs cycle and two consumed in transport of the $NADH_2$ molecules into mitochondria). In aerobic procaryotes, heart, liver, and kidneys, 38 ATP molecules are pro-

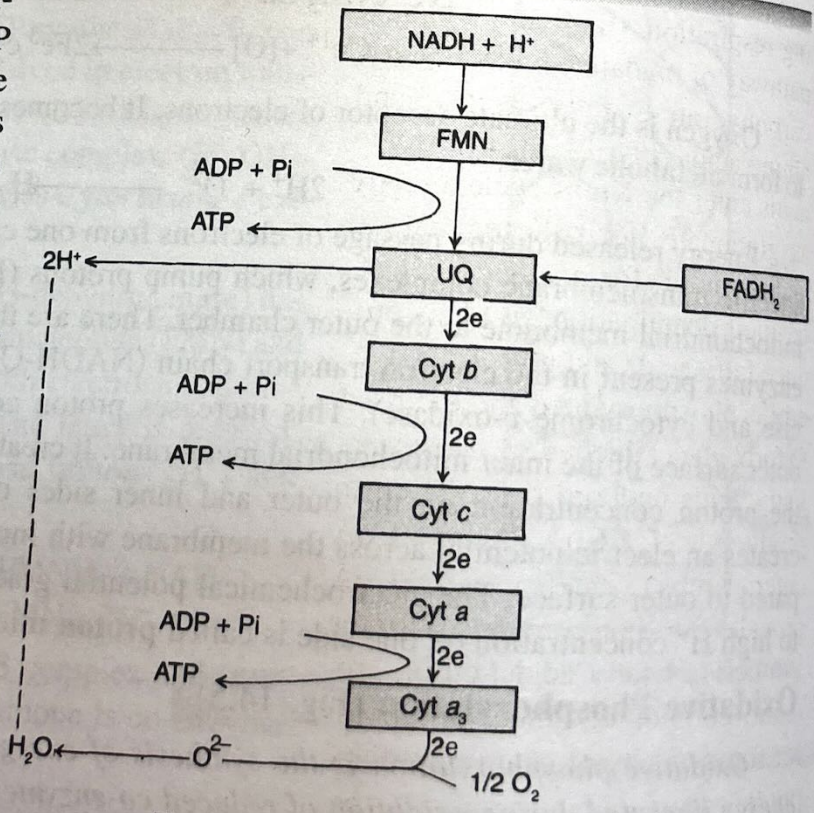


Fig. 14.6. A simplified system of terminal oxidation and oxidative phosphorylation.

duced per glucose molecule oxidised. Passage of ATP molecules from inside of mitochondria to cytoplasm is through facilitated diffusion. Since, one ATP molecule stores 34 kJ or 8.15 kcal/mole (7.6 kcal or 31.8 kJ according to Browse, 1998), the total energy trapped per gm mole of glucose is 1292 kJ or 309.7 kcal with an efficiency of 45%. The rest of the energy is lost as heat.

Stage :	*ATP by substrate phosphorylation*	*Formation of NADH/$FADH_2$*	*ATP through ETS in Mitochondria*
Glycolysis in cytoplasm	2	2 NADH (one NADH on oxidation) through ETS form 3 or 2 ATP depending upon shuttle system	2 × 3 = 6
Formation of Acetyl~CoA in matrix of mitochondria	—	2 NADH	2 × 3 = 6
Krebs cycle	2	2 $FADH_2$	2 × 2 = 4
		6 NADH	6 × 3 = 18
	4		34 (or 32)
Total net gain of ATP = 36 or 38 depending upon type of aerobic respiration.			

Significance of Krebs Cycle and its Intermediates. (i) Krebs cycle is the major pathway for the synthesis of reduced coenzymes and controlled release of energy during respiration. (ii) It is a common pathway of oxidative breakdown of carbohydrates, fatty acids, and amino acids (Fig. 14.7). (iii) Amino acids enter the Krebs cycle directly as glutamate (for α-Ketoglutarate) and asparate (for oxaloacetate) after their deamination. (iv) Fats produce fatty acids and glycerol. Glycerol is phosphorylated and oxidised to form glyceraldehyde 3-phosphate. Fatty acids undergo β-oxidation to produce acetyl CoA. Acetyl CoA enters Krebs cycle. (v) Acetyl CoA provides 2-carbon compounds for the synthesis of fatty acids, cutin, aromatic compounds and isoprenoids for forming phytol chain of chlorophyll, carotenoids, steroids, terpenes, gibberellins, etc. (vi) α-Ketoglutarate of Krebs cycle produces an important amino acid called **glutamate**. (vii) Succinyl CoA takes part in synthesis of pyrrole compounds of chlorophyll, cytochrome

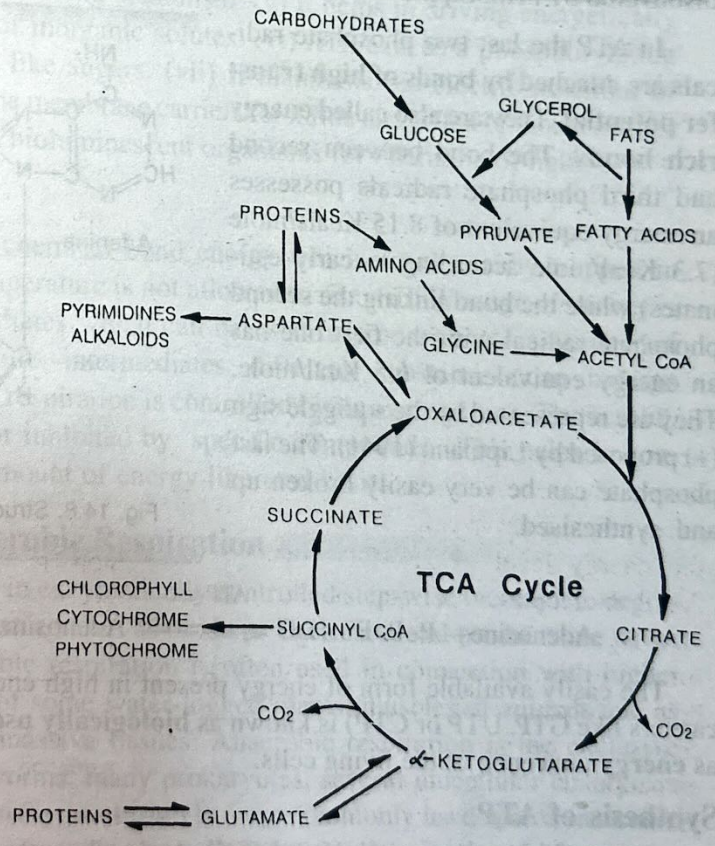


Fig. 14.7. TCA as common metabolic pathway of carbohydrates, fats and proteins.

and phytochrome. (viii) Oxaloacetate produces another important amino acid called aspartate. It also forms pyrimidines and alkaloids. (ix) It forms GTP which is an important component of signal–transduction system. (x) Krebs cycle is **amphibolic** (both catabolic and anabolic) because it provides a number of intermediates for anabolic pathways.

Krebs Cycle— An Amphibolitic Pathway

Amphibolic pathway (Gk. *amphi–* both, *bole–* throw) is the one which is used for both breakdown (catabolism) and build-up (anabolism) reactions. Respiratory pathway is mainly a catabolic process which serves to run the living system by providing energy. The pathway produces a number of intermediates. Many of them are raw materials for building up both primary and secondary metabolites. (i) Acetyl CoA is helpful not only in using fatty acids in Krebs cycle but is also raw material for synthesis of fatty acids, steroids, terpenes, aromatic compounds and carotenoides. (ii) α-ketoglutarate is organic acid which forms glutamate (an important amino acid) on amination. (iii) Oxaloacetate on amination produces aspartate (another important amino acid). (iv) Both aspartate and glutamate are components of proteins. Pyrimidines and alkaloids are other products. (v) Succinyl CoA forms cytochromes and chlorophyll.

ATP (Fig. 14.8)

It is adenosine triphosphate. Adenosine triphosphate is formed of an adenine (a purine), a ribose (a 5-carbon sugar) and a row of three phosphate radicals attached to ribose. The complex formed from adenine and ribose is called **adenosine**. ATP was discovered by Karl Lohmann in 1929. Its functioning through build up and hydrolysis of high energy phosphate bond was discovered by Fritz Lipmann (1941). Lipmann is called father of ATP cycle.

In ATP the last two phosphate radicals are attached by bonds of **high transfer potential**. They are also called **energy rich bonds**. The bond between second and third phosphate radicals possesses an energy equivalent of 8.15 Kcals/mole (7.3 Kcal/mole according to early estimates) while the bond linking the second phosphate radical with the first one has an energy equivalent of 6.5 Kcal/mole. They are represented by the squiggle sign (~) proposed by Lipmann (1941). The last phosphate can be very easily broken up and synthesised.

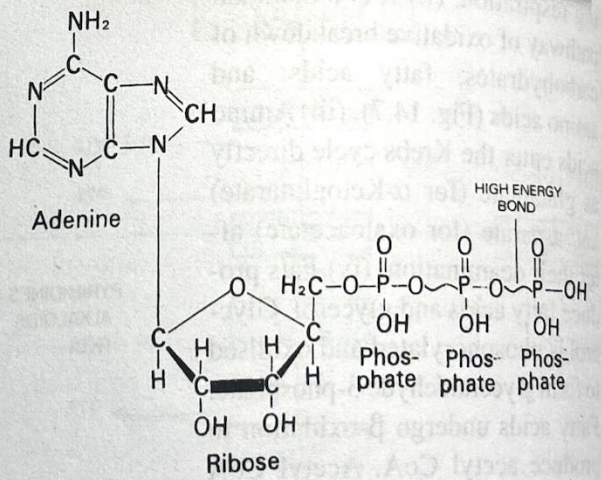


Fig. 14.8. Structure of ATP (Adenosine Triphosphate).

$$\text{Adenosine—P~P~P} + H_2O \xrightleftharpoons{\text{ATP-ase}} \text{Adenosine—P—P} + H_3PO_4 + \text{Energy}$$

The easily available form of energy present in high energy bonds of ATP (and other energy carriers like GTP, UTP or CTP) is known as **biologically useful energy**. Hence ATP can function as **energy currency** of the living cells.

Synthesis of ATP

ATP is synthesised from ADP (adenosine diphosphate) and inorganic phosphate (Pi). The reaction is called **phosphorylation**. It is endergonic or energy requiring. Phosphorylation is of three types— substrate level phosphorylation, oxidative phosphorylation and photophosphory-

lation. Substrate level phosphorylation or ATP synthesis is directly linked to the liberation of energy in chemical reactions of respiration.

$$\text{1 : 3-diphosphoglycerate} + \text{ADP} \rightleftharpoons \text{3-phosphoglycerate} + \text{ATP}$$

$$\text{Phosphoenol pyruvate} + \text{ADP} \longrightarrow \text{Pyruvate} + \text{ATP}$$

$$\text{Succinyl CoA} + \text{ADP} + \text{Pi} \longrightarrow \text{Succinate} + \text{CoA} + \text{ATP}$$

Oxidative phosphorylation is linked to terminal oxidation of reduced coenzymes (NADH and $FADH_2$) in respiration. The coenzymes release H^+ ions and electrons. The electrons pass over a series of carriers, called electron transport chain, before combining with oxygen to make it reactive. The energy released during electron transport is used in creating a proton gradient. The proton gradient activates ATP synthase of F_0–F_1 particles resulting in synthesis of ATP.

Photophosphorylation occurs on the thylakoids of chloroplasts. In the primary photochemical reaction an electron is extruded by chlorophyll *a* on the receipt of radiation energy. The electron passes over a transport chain of carriers. Sufficient energy is released when the electron passes between cytochrome *b* and cytochrome *f* (cyclic photophosphorylation) or plastoquinone to cytochrome *f* (noncyclic photophosphorylation). It creates a proton gradient. The latter activates ATP synthase of F_0–F_1 complex to produce ATP.

Functions. (i) It can store small packets of energy as soon as the energy becomes available so that wastage of energy is minimised. (ii) ATP makes energy available at a spot away from the area of release of energy. (iii) By its accumulation at a spot, it makes available large and continuous supply of energy for carrying out heavy work. (iv) ATP releases small amount of energy required for building new chemical bonds during anabolism. (v) It helps in driving energetically unfavourable processes like absorption of inorganic solutes. (vi) ATP acts as a phosphorylating agent for activating certain metabolites like sugars. (vii) It maintains bio-electric potential of cellular membranes. (viii) ATP energises the membrane carriers for influx and efflux of biochemicals. (ix) It energises the enzyme luciferase in bioluminescent organisms for liberation of light.

Utility of Step-wise Oxidation

(i) There is a step-wise release of chemical bond energy which is very easily trapped in forming ATP molecules. (ii) Cellular temperature is not allowed to rise. (iii) Wastage of energy is reduced. (iv) There are several intermediates which can be used in production of a number of biochemicals. (v) Through their metabolic intermediates different substances can undergo respiratory catabolism. (vi) Each step of respiration is controlled by its own enzyme. The activity of different enzymes can be enhanced or inhibited by specific compounds. This helps in controlling the rate of respiration and the amount of energy liberated by it.

Anaerobic Respiration

It is the process of release of energy in enzymatically controlled step-wise incomplete degradation of organic food without oxygen being used as oxidant. Therefore, end products are never completely inorganic. The term anaerobic respiration is often used in connection with higher organisms where it occurs in the roots of some water-logged plants, muscles of animals and as supplementary mode of respiration in massive tissues. Anaerobic respiration is the exclusive mode of respiration in some parasitic worms, many prokaryotes, several unicellular eukaryotes and moulds. In micro-organisms the term **fermentation** is more commonly used where anaerobic respiration is known after the name of product like **alcoholic fermentation, lactic acid fermentation**. Carbon dioxide is evolved in some cases. It gives a frothy appearance (L. *fermentum* — to boil) to the medium. Buchner (1897) was the first to find that fermentation could be caused

without the living yeast cells by grinding them under pressure and mixing the extract with sugary solution. The enzyme complex present in the extract was named as **zymase**. Because of the latter, fermentation is also called **zymosis**. Commonly, *fermentation is defined as the anaerobic breakdown of carbohydrates and other organic compounds into alcohols, organic acids, gases, etc. with the help of micro-organisms or their enzymes.*

The mechanism of anaerobic respiration or fermentation is similar to common pathway of aerobic respiration upto glycolysis. Glycolysis breaks down glucose enzymatically in several steps to form two molecules of pyruvate, 2 ATP and 2 NADH ($+H^+$). Pyruvate is anaerobically broken down to yield various products depending upon the organism and the type of tissue. The two common products are ethyl alcohol and lactic acid.

1. **Ethyl Alcohol Fermentation** (Fig. 14.9). It is quite common in fungi (*e.g., Rhizopus,* Yeast) and bacteria. Yeast can respire both aerobically and anaerobically. Anaerobic respiration occurs in sugary solution if the fungus is not in contact with atmosphere. It causes fermentation. In the presence of pyruvate decarboxylase and TPP (thiamine pyrophosphate), pyruvate is broken down to form acetaldehyde. Carbon dioxide is released.

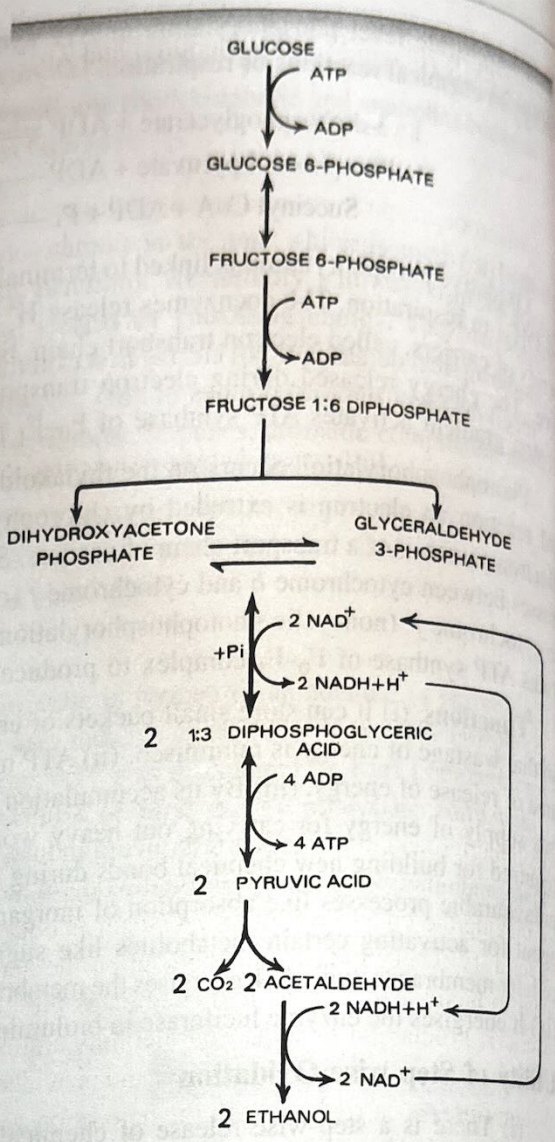


Fig. 14.9. Schematic representation of alcoholic fermentation or anaerobic respiration yielding ethyl alcohol.

$$\text{Pyruvate} \xrightarrow[\text{Decarboxylase, TPP, } Mg^{2+}]{\text{Pyruvate}} \text{Acetaldehyde} + CO_2 (\uparrow)$$

Acetaldehyde is reduced to ethyl alcohol or ethanol by alcohol dehydrogenase. Hydrogen is obtained from NADH produced during oxidation of glyceraldehyde 3-phosphate to 1 : 3 diphosphoglycerate in glycolysis.

$$\text{Acetaldehyde} + \text{NADH} \xrightarrow[\text{dehydrogenase}]{\text{Alcohol}} C_2H_5OH + NAD^+$$

Ethyl alcohol does not stay inside microorganisms but is excreted. Accumulation of alcohol beyond a certain limit can, however, kill the microorganism (*e.g.,* 13% in yeast). A higher concentration of alcohol in a beverage is achieved through distillation.

2. **Lactic Acid Fermentation.** The fermentation occurs in lactic acid bacteria (*e.g., Lactobacillus*), some fungi and muscles. Lactic acid produced in muscles is sent to liver to regenerate glucose. In lactic acid fermentation pyruvic acid produced in glycolysis is directly reduced by

NADH to form lactic acid. No CO_2 is produced. The enzyme is lactic dehydrogenase which requires FMN (Flavin Mono-nucleotide) and Zn^{2+}.

$$\text{Pyruvic Acid} + \text{NADH} \xrightarrow[\text{FMN, } Zn^{2+}]{\text{Lactic dehydrogenase}} \text{Lactic Acid} + NAD^+$$

Anaerobic respiration produces very little energy (about 5%) as compared to aerobic respiration. The reasons are (a) There is incomplete breakdown of respiratory substrate. (b) Atleast one of the products of anaerobic respiration is organic. It can be further oxidised to release energy. (c) NADH produced during glycolysis is often used up. (d) ATP formation does not occur during regeneration of NAD^+. (e) Electron transport chain is absent. (f) Oxygen is not used for receiving electrons and protons.

Differences between Anaerobic Respiration and Fermentation

Anaerobic Respiration	*Fermentation*
1. It is a type of respiration.	1. It is enzyme controlled breakdown and transformation of organic nutrients.
2. It is an intracellular process.	2. It is both intracellular and extracellular process.
3. It is not economically exploited.	3. It is economically exploited.

Importance. (i) Anaerobic respiration is important during periods of oxygen deficiency. (ii) Alcoholic fermentation is used in brewing industry for the production of various types of beers, whisky and other wines. (iii) Carbon dioxide of alcoholic fermentation is used in baking industry for making the bread spongy. (iv) Vinegar is obtained by the fermentation activity of acetic acid bacteria. (v) Dairy industry depends upon the action of lactic acid bacteria which convert milk sugar to **lactic acid**. Lactic acid coagulates the milk protein casein and the droplets of milk fat fuse. (vi) Production of industrial alcohols and organic acids. (vii) Tea and tobacco leaves are cured (or removed of their bitterness) and provided with a fine flavour. (viii) Retting or separation of stem fibres is carried out with the help of bacterial fermentation of softer tissues. (ix) Ensilage or preserved fodder is prepared by keeping green chopped fodder in silo where bacterial action causes softening and release of preserving acids. (x) Cleaning of raw hides is a fermentative bacterial activity. (xi) Decomposition of organic remains is carried out by fermentation. However, the fermenting organisms also spoil out food and may cause food poisoning by releasing toxins or ptomains.

Differences between Glycolysis and Fermentation

Glycolysis	*Fermentation*
1. It is the first step of respiration which occurs without requirement of oxygen and is common to both aerobic and anaerobic modes of respiration.	1. It is anaerobic respiration or respiration which does not require oxygen.
2. Glycolysis produces pyruvic acid.	2. Fermentation produces different products. The common ones are ethanol (and CO_2) and lactic acid.
3. It produces two molecules of NADH per glucose molecule.	3. It, generally, utilises NADH produced during glycolysis.
4. Glycolysis forms 2 ATP molecules per glucose molecule.	4. It does not produce ATP.

Differences between Aerobic Respiration and Fermentation or Anaerobic Respiration

Aerobic Respiration	*Fermentation or Anaerobic Respiration*
1. It involves exchange of gases.	1. An exchange of gases is absent.
2. It uses oxygen for breaking the respiratory material into simple substances.	2. Oxygen is not used in the breakdown of respiratory substrate.
3. Respiratory material is completely oxidised.	3. Respiratory material is incompletely broken.
4. The end products are inorganic.	4. At least one of the end products is organic.
5. Aerobic respiration is the normal mode of respiration of plants and animals.	5. It is the normal mode of respiration in some parasitic worms and micro-organisms. In others. It is a stop-gap arrangement.
6. Aerobic respiration involves electron transport.	6. Electron transport is absent.
7. Aerobic respiration consists of three steps— glycolysis, Krebs cycle and terminal oxidation.	7. Anaerobic respiration consists of two steps— glycolysis and incomplete break-down of pyruvic acid.
8. Every carbon atom of the food is oxidised and a large quantity of CO_2 is evolved.	8. Less quantity of carbon dioxide is evolved.
9. It requires the assistance of mitochondria.	9. Mitochondria are not required.
10. Water is formed.	10. Water is usually not formed.
11. 686 kcal of energy are produced per gm mole of glucose.	11. Only 39–59 kcal of energy are formed per gm mole of glucose.
12. It continues indefinitely.	12. Anaerobic respiration cannot continue indefinitely (except in some micro-organisms) because of the accumulation of poisonous compounds and less availability of energy per gm mole of food broken.

Experiment 1. Demonstration of Aerobic Respiration ***(or oxygen is used up and carbon dioxide is produced during aerobic respiration).***

Apparatus. Two sets of conical flasks, delivery tubes bent twice at right angles, corks, beakers containing coloured water, small test tubes containing 20% potassium hydroxide solution, thread, soaked and dry seeds, melted wax or vaseline.

Working. Put some germinating seeds in a conical flask (living animals, flower buds etc. can also be used). The conical flask is fitted to a delivery tube bent twice at right angles by means of cork. Suspend a small test tube containing 20% potassium hydroxide solution in the flask by means of a thread. Dip the free end of the bent tube in a beaker of coloured water. Make the connections air tight (Fig. 14.10 A). Prepare another set of apparatus but with dry seeds (Fig. 14.10 B). Note that after some time coloured water rises in the tube of the apparatus having soaked seeds while there is no such change in the level of water in the second apparatus.

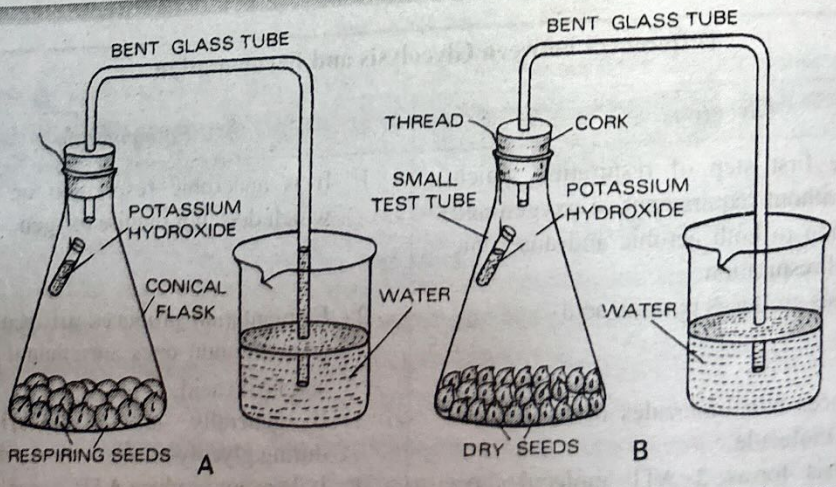


Fig. 14.10. Demonstration of aerobic respiration. A, respiring seeds. B, dry seeds.

Results. Only germinating seeds respire aerobically. Oxygen required for this is taken up from the air of the apparatus. Carbon dioxide released during aerobic respiration is absorbed by potassium hydroxide. Therefore, a partial vaccum is created in the conical flask. This causes the rise of water in the bent tube. That oxygen is consumed during aerobic respiration can be tested by taking a burning splinter into the flask. It gets extinguished.

Precautions (i) The seeds should be actually germinating (with broken seed coat) and not recently soaked seeds. If the flower buds are to be used in the experiment, green pedicels and sepals must be removed. (ii) The apparatus should be air tight. (iii) The free end of the bent glass tube should be placed in water prior to applying vaseline for making the connections air tight. (iv) The end of bent tube present inside the conical flask should be well above the seeds.

Experiment 2. Demonstration of Anaerobic Respiration.

Apparatus. A test tube of hard glass, a deep petri dish or beaker of hard glass, mercury, soaked and peeled seeds of pea or gram, potassium hydroxide stick or pellet, forceps, stand.

Working. Invert a hard glass test tube full of mercury over a petri dish containing mercury. Slightly lift the test tube from the bottom of the dish (do not take it out of the mercury level) and introduce into its mouth a few soaked and peeled seeds of pea or gram by means of forceps. The seeds will rise upwards (Fig. 14.11 A).

After some interval, the level of mercury will fall in the test tube showing that some gas has collected there (Fig. 14.11 B). Introduce in the test tube a potassium hydroxide stick by means of forceps. The level of mercury will rise again.

Results. In the test tube full of mercury there is no air and, therefore, the introduced soaked seeds do not get air for their respiration. But they are capable of respiration in the absence of oxygen as is indicated by the evolution of a gas. The gas is carbon dioxide because it can be absorbed by potassium hydroxide forming potassium carbonate and water. Therefore, anaerobic respiration takes place in the seeds in the absence of free oxygen. The experiment also shows that carbon dioxide is evolved in anaerobic respiration of seeds.

Precautions. (i) The mouth of the test tube must be smooth. (ii) The dish for mercury should be deep. (iii) While inverting the test tube of mercury, close its mouth by your thumb. (iv) The seeds should be well soaked so that they are respiring actively. (v) Do not touch potassium hydroxide with hand. Replace the cover of its bottle immediately after taking out the required pellet or stick.

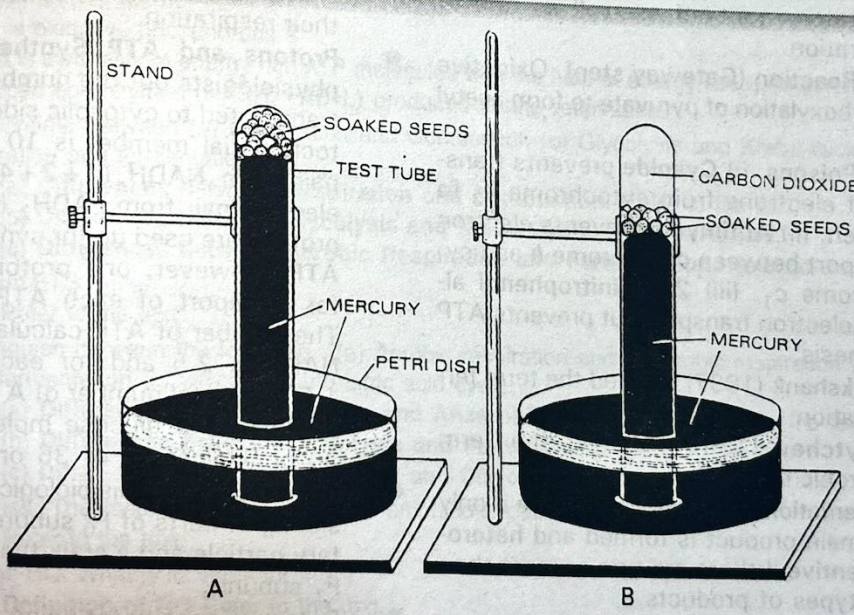


Fig. 14.11. Demonstration of anaerobic respiration. A, at the beginning of experiment. B, evolution of gas by anaerobically respiring seeds.

Experiment 3. Study the products of anaerobic respiration in yeast.

Apparatus. Yeast culture or baker's yeast, a large test tube with single holed cork, a small test tube of lime water with single holed cork, 10% glucose solution, nondrying oil, iodine solution, 10% NaOH solution, wax or vaseline, twice bent glass delivery tube, large beaker, warm water.

Preparation of Yeast Culture. Prepare Pasteur solution with following composition : Sugar— 75 gm,

Ammonium tartrate— 5 gm, Potassium sulphate— 1 gm, Magnesium sulphate— 0.1 gm, Calcium sulphate— 0.1 gm, Water— 419 ml. The solution is placed in a sterilised flask. A tea spoon full of baker's yeast or a small piece of yeast cake is dissolved in the solution. The mouth of the flask is plugged with cotton. It is then kept in a warm place. The culture will have numerous yeast cells within two days.

Working. Take 10 ml of 10% glucose solution in a large test tube. Add 5 ml of yeast culture or a pinch of baker's yeast. Pour 3–5 drops of nondrying oil (like mustard oil) to cover the solution and provide an anaerobic environment to yeast cells. The mouth of the test tube is covered with a single holed cork. The test tube is now connected to a small corked test tube having lime water by means of a twice bent glass delivery tube. Connections are made air tight by vaseline or melted wax. The larger test tube is warmed to 37–38°C by dipping it partially in a beaker having warm water. Bubbles of gas are found to come out of the covered yeast solution in the larger test tube. It enters the smaller test tube through the delivery tube and turns the lime water milky. Lime water does not rise in the delivery tube showing that oxygen of the internal atmosphere of the apparatus is not being consumed in respiration of yeast. The latter is purely anaerobic.

Result. The turning of lime water into milky solution shows that carbon dioxide is being produced in anaerobic respiration of yeast.

Remove the cork of the larger test tube and take out the small quantity of solution by means of a dropper. It smells of alcohol. Test the solution chemically for alcohol by taking 5 ml of it in a test tube, pouring four drops of 10% NaOH solution and iodine solution drop by drop till it turns faintly yellow. Allow it to stand for two minutes, shake and find the presence of insoluble yellowish iodoform at the bottom.

Therefore, both carbon dioxide and ethyl alcohol are produced during anaerobic respiration.

Precautions. (i) Check the presence of yeast cells in the culture solution. (ii) Seal the joints air tight by wax or vaseline. (iii) Keep the end of the twice bent delivery tube well above the solution in the large test tube while the other end should completely dip inside lime water. (iv) Keep the larger test tube in warm water.

ADDITIONAL INFORMATION

- **Respirometer.** Instrument for measuring respiratory quotient as well as rate of respiration.
- **Link Reaction** (Gateway step). Oxidative decarboxylation of pyruvate to form acetyl CoA.
- **ETC Poisons.** (i) **Cyanide** prevents transfer of electrons from cytochrome a_3 to oxygen. (ii) **Antimycin** prevents electron transport between cytochrome *b* and cytochrome c_1. (iii) **2:4 Dinitrophenol** allows electron transport but prevents ATP synthesis.
- **Cruickshank** (1897). Coined the term fermentation.
- **Kostytchev** (1902). Coined the term anaerobic respiration.
- **Fermentation.** It is **homofermentive** if only one main product is formed and **heterofermentive** if there are two or more than two types of products.
- **Lactic Acid and Heart.** Heart muscles have enzyme to convert lactic acid into pyruvate. During heavy excercise, lactic acid is formed in large quantities by skeletal muscles. The same is poured into blood. A part of it is used by heart muscles in order to obtain extra energy for rapid activity.
- **Fatty Acids in Muscles.** If both fatty acids and carbohydrates are available to muscles, the latter will first consume fatty acids in their respiration.
- **Protons and ATP Synthesis.** Modern physiologists put the number of protons transported to cytosolic side of inner mitochondrial member is 10 per electron pair from NADH (4+2+4) and 6 per electron pair from $FADH_2$ (2+4). Three protons are used up for synthesis of one ATP. However, one proton is required for transport of each ATP to cytosol. The number of ATP calculated for each NADH is 2.5 and for each $FADH_2$ as 1.5. The total number of ATP molecules produced per glucose molecule is then 30 or 32 instead of 36 or 38.
- **Smallest Motor.** It is biological motor consisting of parts of F_0 subunit of elementary particle and a stalk that passes into F_1 subunit.
- **Energy.** Capacity for doing work. **Potential Energy.** Energy stored due to position or chemical bonds. **Kinetic Energy.** Energy in action or possessed by moving objects.
- **Dutrochet.** Coined the term respiration.
- **Pasteur Effect.** Reduction in consumption of respiratory substrate when the mode of respiration is changed from anaerobic to aerobic.

NCERT TEXTBOOK QUESTIONS WITH ANSWERS

1. What are respiratory substances ? Name the most common respiratory substrate.
   ✔ **Respiratory substrates** are organic substances which are oxidised during respiration to liberate energy inside living cells.
   Most Common Respiratory Substrate. Glucose.
2. Give the schematic representation of glycolysis.
   ✔ Fig. 14.2.
3. What are the main steps in aerobic respiration ? Where do they take place ?
   ✔ Aerobic respiration occurs in four steps — glycolysis, link reaction, Krebs cycle and terminal oxidation.
   Glycolysis. It is a partial oxidation of glucose to form two molecules of pyruvate, two NADH and two ATP. Glycolysis occurs in cytoplasm.
   Link Reaction (Oxidative Decarboxylation). After entering mitochondria, pyruvate undergoes oxidative decarboxylation to form acetyl CoA and NADH. CO_2 is released.
   Krebs Cycle (Tricarboxylic Acid Cycle). Acetyl CoA reacts with oxaloacetate. The product, citrate, undergoes two oxidative decarboxylations and two dehydrogenations. Oxaloacetate is regenerated. The products are 3NADH, 1$FADH_2$, 1ATP or GTP and 2 CO_2. Krebs Cycle occurs inside mitochondria.
   Terminal Oxidation. NADH and FADH are oxidised. Energy liberated during oxidation is used in synthesis of ATP from ADP and inorganic phosphate. Hydrogen is ultimately oxidised by oxygen to form water. Terminal oxidation takes place over the inner membrane of mitochondria.
4. Give the schematic representation by an overall view of Krebs Cycle.
   ✔ Fig. 14.3.
5. What are the assumptions made during the calculation of net gain of ATP ?
   ✔ NADH produced inside mitochondria helps in synthesis of 3 ATP molecules during its oxidation.
   $FADH_2$ produced inside mitochondria forms 2ATP molecules during its oxidation.
   NADH formed during glycolysis sends its reducing power into mitochondria through shuttle system. It forms 3ATP in malate-asparate shuttle (heart, liver, kidney) and two ATP in glycerol phosphate shuttle (muscles and nerve cells).
6. What is oxidative phosphorous ?
   ✔ It is synthesis of energy rich ATP molecules with the help of energy liberated during oxidation of reduced co-enzymes (NADH, $FADH_2$) produced during respiration.
7. Differentiate between (a) Respiration and Combustion (b) Glycolysis and Krebs cycle (c) Aerobic respiration and fermentation.
   ✔ (a) **Differences between Respiration and Combustion**. Refer to the text.
   (b) **Differences between Glycolysis and Krebs Cycle**. Refer to the text.
   (c) **Differences between Aerobic Respiration and Fermentation**. Refer to the text.
8. Explain ETS
   ✔ Refer to the text.
9. Distinguish between the following : (a) Aerobic respiration and anaerobic respiration (b) Glycolysis and fermentation (c) Glycolysis and citric acid cycle.
   ✔ (a) **Differences between Aerobic and Anaerobic Respiration**. Refer to the text.
   (b) **Differences between Glycolysis and Fermentation**. Refer to the text.
   (c) **Differences between Glycolysis and Citric Acid Cycle**. Refer to the text.
10. Discuss "The respiratory pathway is an amphibolic pathway".
    ✔ Refer to the text.
11. Define RQ. What is its value for fats ?
    ✔ **Definition of RQ** Refer to the text.
    RQ. for Fats — 0.7
12. What is the significance of step-wise release of energy in respiration ?
    ✔ Refer to the text.

TEST QUESTIONS

One Mark Questions (With Answers)

1. Define cellular respiration ?
   ✔ Cellular respiration is an energy releasing enzymatically controlled catabolic process which involves a step-wise oxidative breakdown of organic substances inside living cells.

2. Name the most common respiratory substrate ?
   ✔ **Glucose.**
3. What is net ATP production in glycolysis ?
   ✔ 2 ATP.
4. Which enzyme is required for the synthesis of ATP ?
   ✔ **ATP synthetase**
5. What is zymosis ?
   ✔ Zymosis is the alternate name of fermentation which has been coined after the name of fermentation causing enzyme complex **zymase** of yeast.
6. Which type of respiration results in the formation of water ?
   ✔ Water is formed in Aerobic respiration.
7. What is the final product of glycolysis - pyruvic acid/glucose/malic acid/phosphoglyceric/Acetyl CoA/ Phosphoric acid.
   ✔ Pyruvic acid.

Two Mark Questions (With Sample Answer)

8. Why can red muscle fibres work for longer periods continuously ?
   ✔ Red muscle fibres contain abundant myoglobin, the pigment which stores oxygen. White muscle fibres have little of myoglobin. Red muscle fibres can, therefore, continue work over long periods by using myoglobin stored oxygen and hence performing aerobic respiration.
9. How proton gradient is established ?
10. Complete oxidation of 1 gm mole of glucose yields (a) 686 cal (b) 6860 cal (c) 68600 cal (d) 686000 cal.
11. What is meant by Respiration Quotient (RQ) ? When will the value of RQ be 1 and when will it be less than 1 ?

Three Mark Questions (Short answer type)

12. Write explanatory notes on: (a) Glycolysis (b) fermentation by yeast (c) electron transport chain.
13. Explain the main steps in aerobic respiration.
14. What is respiratory substrate? Enumerate the steps involved in the breakdown of carbohydrates upto pyruvic acid.
15. Mitochondria are called the power houses of the cell. Which of the followinig observations supports this statement ?
    (a) mitochondria contain ATP
    (b) mitochondria have a double membrane
    (c) the enzyme of the Krebs cycle and the cytochromes are found in mitochondria.
    (d) mitochondria are found in almost all kinds of plant and animals cells.

Five Mark Questions (Long answer type)

16. How are glycolysis, Krebs TCA cycle and the electron transport chain linked?
17. How would you demonstrate that yeast can respire both aerobically and anaerobically ?
18. (a) Give a schematic respiration of Krebs cycle. List the enzymes involved in each step.
    (b) Mention the steps in Krebs cycle in which NAD and FAD are reduced while accepting hydrogen from different substrates.
19. (a) Define R.Q What is its significsance ?
    (b) Explain these terms in 3-4 lines: Anearobic respiration, glycolysis, cristae, oxidative phosphorylation. Elementary particles, Coenzymes. Energy currency of cells.
20. What is anaerobic respiration ? How would you demonstrate it experimentally ?
21. Explain the major steps of Glycolysis. Where does this process occur in a cell ?

Miscellaneous Questions

22. Fill in blanks
    (a) Acetyl-CoA is formed from _____ and coenzyme A.
    (b) In procaryotes _____molecules of ATP are formed per molecule of glucose oxidised.
    (c) Glycolysis takes place in _____.
    (d) $F_0 - F_1$ particles participate in the synthesis of _____.
    (e) During glycolysis _____ molecules of NADH are formed.

23. (i) When and where does anaerobic respiration occur in man and yeast ?
(ii) Why is less energy produced during anaerobic than in aerobic respiration ?
(iii) Where is the respiratory electron transport system located in a cell ?
(iv) What compound is the terminal electron acceptor in aerobic respiration ?

Multiple Choice Questions

(1) Anaerobic respiration of Yeast produces (a) N_2 (b) O_2 (c) CO_2 (d) H_2O *(AFMC 2000)*

(2) R.Q. is more than one in case the substrate is (a) Fat (b) Glucose (c) Protein (d) Organic acid. *(MPPMT 2000)*

(3) Metabolism of one plamitic acid molecule yields (a) 36 ATP (b) 56 ATP (c) 48 ATP (d) 136 ATP. *(CBSE 2000)*

(4) RQ is less than unity in case of (a) Starch (b) Organic acid (c) Carbohydrate (d) Protein. *(Raj PMT 2002)*

(5) Fermentation is (a) Anaerobic respiration (b) Incomplete oxidation (c) Excretory process (d) None of the above. *(Raj PMT 2002)*

(6) At the end of citric acid cycle, most of the energy is transferred to (a) Oxaloacetic acid (b) NADH and $FADH_2$ (c) ATP (d) Citric acid. *(AMU 2002)*

(7) RQ of sprouting Patato is (a) Zero (b) > 1 (c) 1 (d) < 1 *(Karnataka 2002)*

(8) The last electron acceptor of ETC during oxidative phosphorylation is (a) Cyt *b* (b) $Cyta_3$ (c) H_2 (d) CO_2 *(AIIMS 2002)*

(9) Before combining with oxaloacetate, pyruvate is changed into (a) Acetyl CoA (b) Citric acid (c) Malic acid (d) Succinic acid *(BHU 2002)*

(10) Glycolysis occurs in (a) nerve cells (b) muscle cells (c) eucaryotic cells (d) all cells. *(AFMC 2003)*

(11) Two synonyms are (a) Citric acid and Calvin cycle (b) Tricarboxylic acid cycle and citric acid cycle (c) Krebs cycle and Calvin cycle (d) Tricarboxylic acid cycle and urea cycle. *(CBSE 2003)*

(12) Dough kept overnight in warm place becomes soft and spongy due to (a) osmosis (b) absorption of CO_2 (c) cohesion (d) fermentation. *(CBSE 2004)*

(13) Number of glucose molecules required to produce 38 ATP molecules under anaerobic conditions is (a) 2 (b) 4 (c) 19 (d) 38. *(Kerala 2004)*

(14) Pasture effect can be studied in case of (a) *Nostoc* (b) *Penicillium* (c) *Pinnularia* (d) *Saccharomyces.* *(Karanataka 2004)*

(15) In glycolysis, electrons are removed by (a) ATP (b) NAD (c) Glyceraldehyde 3-phosphate (d) Molecular oxygen. *(CBSE 2004)*

(16) Cell respiration is carried out by (a) Mitochondria (b) Golgi bodies (c) Ribosomes (d) Chloroplasts. *(Orissa 2004)*

(17) What is R.Q. of the reaction : $2\ (C_{51}H_{98}O_6) + 146\ O_2 \rightarrow 102\ CO_2 + 98\ H_2O$? (a) 0.7 (b) 1.0 (c) 1.45 (d) 1.62. *(Manipal 2005)*

(18) Chemiosmotic theory of ATP synthesis in chloroplasts and mitochondria is based on (a) membrane potential (b) accumulation of Na^+ ions (c) accumulation of K^+ ions (d) proton gradient. *(CBSE 2005)*

(19) During which stage in the complete oxidation of glucose are the greatest number of ATP molecules formed from ADP ? (a) Glycolysis (b) Krebs cycle (c) Electron transport chain (d) Conversion of pyruvic acid to acetyl CoA. *(CBSE 2005)*

(20) How many NADH molecules are produced when four molecules of phosphoglyceraldehyde are converted into four molecules of pyruvate. (a) 2 (b) 4 (c) 6 (d) 8. *(Bih. PMT 2006)*

(21) Which process makes direct use of oxygen ? (a) Glycolysis (b) Fermentation (c) Electron transport (d) Krebs cycle. *(Kerala 2006)*

(22) Lactic acid is formed by the process of (a) Fermentation (b) Krebs cycle (c) HMP (d) Glycolysis. *(DPMT 2007)*

(23) In Krebs cycle, acetyl CoA forms 6-carbon compound after combining with (a) citric acid (b) malic acid (c) oxaloacetic acid (d) succinic acid. *(BHU 2007)*

(24) Overall goal of glycolysis, Krebs cycle and electron transport system is formation of (a) ATP in small stepwise units (b) sugars (c) nucleic acid (d) ATP in one large oxidation reduction reaction. *(CBSE 2007)*

(25) Cellular respiration first takes place in (a) Cytoplasm (b) ER (c) Lysosomes (d) Golgi bodies. *(DPMT 2008)*

(26) Net gain of ATP molecules per hexose during aerobic respiration is (a) 12 (b) 18 (c) 36 (d) 30. *(DPMT 2008)*

(27) Energy releasing process in which the substrate is oxidised without an external electron acceptor is (a) Glycolysis (b) Fermentation (c) Photorespiration (d) Aerobic respiration. (CBSE 2009)

(28) Oxidative phosphorylation is (a) Anaerobic production of ATP (b) Citric acid production of ATP (c) Production of ATP by chemiosmosis (d) Alcoholic fermentation. (DPMT 2009)

(29) Aerobic respiratory pathway is appropriately called (a) Anabolic (b) Catabolic (c) Amphibolic (d) Parabolic. (CBSE 2009)

(30) Respiratory quotient (RQ) for fat tripalmitin is (a) 0.9 (b) 1.0 (c) 1.4 (d) 0.7. (HPMT 2010)

(31) FAD^+ is reduced during conversion of (a) citric acid to isocitric acid (b) isocitric acid to α -ketoglutaric acid (c) α -ketoglutaric acid to succinyl CoA (d) Succinic acid to fumaric acid. (AFMC 2010)

(32) RQ of protein is (a) 0.7 (b) 1.0 (c) 0.9 (d) more than one. (HP PMT 2011)

(33) In mitochondria, protons accumulate in (a) Outer membrane (b) Intermembrane space (c) Inner membrane (d) Matrix. (Bih PMT 2011; CBSE Mains 2011)

Assertion and Reason Type Questions

In each of the following questions two statements are given, one is Assertion (A) and other is Reason (R). For the (A) and (R) statements, mark the correct answer as–

*(A) If both **A** and **R** are true and **R** is the correct explanation of **A***

*(B) If both **A** and **R** are ture and **R** is not the correct explanation of **A***

*(C) If **A** is true but **R** is false*

*(D) If both **A** and **R** are false.*

(1) **Assertion.** In a girdled plant, roots begin to perform protoplasmic respiration
Reason. Protoplasmic respiration occurs only under starvation conditions.
(A) (B) (C) (D)

(2) **Assertion.** Gateway reaction of respiration is oxidative decarboxylation of pyruvate.
Reason. The reaction allows the product to enter mitochondria.
(A) (B) (C) (D)

(3) **Assertion.** Krebs cycle is called tricarboxylic acid cycle.
Reason. The first product of krebs cycle is citric acid which is tricarboxylic in nature.
(A) (B) (C) (D)

(4) **Assertion.** Respiratory enzyme found attached to inner mitochondrial membrane is malate dehydrogenase.
Reason. It allows acetyl CoA to enter Kreb cycle
(A) (B) (C) (D)

(5) **Assertion.** In mature cells hexose monophosphate, shunt replaces glycolysis
Reason. Glycolysis is a slow process which cannot feed mitochondria with raw materials.
(A) (B) (C) (D)

(6) **Assertion.** Krebs cycle is amphibotic.
Reason. Krebs cycle produces maximum amount of ATP energy.
(A) (B) (C) (D)

(7) **Assertion.** Fermentation is called zymosis
Reason. It is based on enzyme complex zymase.
(A) (B) (C) (D)

(8) **Assertion.** Proton gradient is required for ATP synthesis.
Reason. Two protons entering an elementary particle knocks out one oxygen of phosphate to make it energy rich reactive phosphate for combining with ADP.

ANSWERS

22. (a) acetate (b) 38 (c) cytoplasm (d) ATP (e) Two
23. (i) Muscles in human beings and submergence in surgary solution in yeast (ii) Incomplete breakdown of respiratory substrate (iii) Inner mitochondrial membrane (iv) Oxygen.

Multiple Choice Questions

1 —(c) 2 —(d) 3 —(d) 4 —(d) 5 —(a) 6 —(b) 7 —(c) 8 —(b) 9 —(a) 10 —(d)
11 —(b) 12 —(d) 13 —(c) 14 —(d) 15 —(b) 16 —(a) 17 —(a) 18 —(d) 19 —(c) 20 —(b)
21 —(c) 22 —(a) 23 —(c) 24 —(a) 25 —(a) 26 — (c) 27 —(b) 28 —(c) 29 —(c) 30 —(d)
31 —(d) (32) —c (33) —b

Assertion and Reason Type Questions

1 —(A) 2 —(C) 3 —(A) 4 —(D) 5 —(D) 6 —(B) 7 —(A) 8 —(A)